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ESTIMATION OF DYNAMIC (WINDBLAST) PRESSURE
ON AIRCREWMAN EJECTION SYSTEMS

Thomas J. Zenobi
Aircraft and Crew Systems Directorate
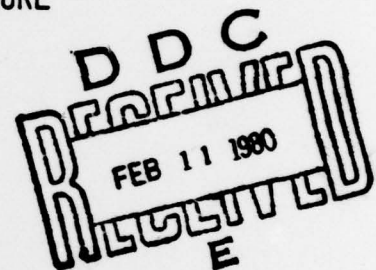NAVAL AIR DEVELOPMENT CENTER
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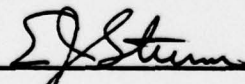AIRTASK NO. F41400000
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Shock Wave Effects
Ejection Systems

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is intended to help designers and engineers, primarily involved in the design of aircraft ejection systems, understand and estimate windblast pressure. Effects of windblast pressure are addressed for a range of sonic velocities. Windblast pressure curves for various altitudes are included.

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DISCUSSION

CALCULATING DYNAMIC PRESSURE (WINDBLAST) FOR SUBSONIC VELOCITIES

Ejection seat designers who are concerned with windblast effects have seen the following equation used for calculating dynamic pressure, q.

$$q = 1/2\rho V^2 \tag{1}$$

where

ρ = local atmospheric density

V = velocity of the body.

This familiar equation is the Bernoulli equation for <u>incompressible</u> flow. Note that the implication of incompressible flow makes the equation valid for low subsonic speeds only. For speeds greater than Mach No. 0.4 compressibility effects of air must be taken into account.

For Mach numbers ranging from 0.4 to 1.0 the dynamic pressure can be calculated from the following equation, references (a) and (b).

$$q_c = p \left[\left(1 + \frac{\gamma-1}{2} M^2\right)^{\gamma/(\gamma-1)} - 1 \right] \tag{2}$$

where

$\overline{p}$ = static pressure or local pressure at altitude

γ = compressibility-related gas constant (for air, γ = 1.4)

Substituting for γ, equation (2) becomes

$$q_c = p \left[(1 + .2M^2)^{3.5} - 1\right] \tag{3}$$

If q is calculated for Mach 1 at sea level using equation (1), the q would be calculated to be about 1480 lb/ft². However, taking into account compressibility effects and using equation (3), q is calculated to be about 1890 lb/ft², a percentage difference of 22 percent. Therefore, use of the incompressible equation introduces significant error for dynamic pressure calculations for high-subsonic flow.

It should be noted and clarified that equation (2) is valid for the entire subsonic range and can be used in place of equation (1) for low subsonic flow.

ESTIMATING DYNAMIC PRESSURE (WINDBLAST) FOR SUPERSONIC VELOCITIES

The formation of shock waves about an object moving at speeds of near Mach 1 and higher complicates the calculation of dynamic pressure. A shock

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wave produces a change in the local properties of the air; before-shock values and after-shock values of windstream velocity, pressure and temperature are different. Greater changes in local properties occur across the shock wave as the intensity of the shock becomes greater.

There are three shock formations to consider: a) normal compression, b) oblique compression, c) Prandtl-Meyer expansion, {references (a) and (b)}. A normal shock occurs when shock wave formation is perpendicular (or normal) to the freestream flow. Such a condition may exist when a detached shock wave forms in front of a blunt body moving at supersonic speed. The detached shock can be assumed as a normal shock wave in the immediate area of the blunt body. See figure 1. Freestream velocity across a normal compression shock decreases to a subsonic level. Along with the decrease in velocity, V, there is an increase in static pressure, p, density, ρ, and static temperature, T. The shock formation is considered to be isentropic and stagnation temperature, T_t, remains constant. The change of properties before the shock wave to behind the shock wave occurs as an almost discontinuous change in fluid properties. Figure 2 depicts a section of a normal shock and its characteristics.

An oblique compression shock is similar to the normal shock except for its orientation to the freestream and its magnitude of V_2. The oblique shock forms at an angle to the freestream and the velocity, V_2, behind the wave, although less than V_1, may be supersonic or subsonic. The formation of oblique compression shock waves can be caused by the presence of a wedge or cone in the supersonic windstream, as shown in figure 3.

For the Prandtl-Meyer expansion, the change in magnitude of properties across the wave are opposite the changes that occur across a compression shock. The expansion occurs when the supersonic stream flows across a convex contour, as shown in figure 4. The expansion cannot reinforce itself as a compression shock does to form a shock wave; the expansion is fan-shaped and not a true wave. For simplicity, it can be depicted as shown in figure 5; the variation of flow properties is also indicated. Like the compression shock, the Prandtl-Meyer expansion can be assumed to be an isentropic process.

The shape of the object and airspeed determine the shape of the shock wave. Detached shocks occur when the change of shape contour is too severe for the airstream to undergo a smooth adjustment. Shock formations can also form on an object even though the object is traveling at a speed less than Mach 1. Shock waves may then occur where local velocities on surface contours increase to speeds greater than Mach 1.

For purposes of estimating dynamic pressures on an ejecting crewman and ejection system at supersonic speed, it is assumed that the shock formation is that of a detached shock in front of a blunt body. The properties of the windstream which affect the crewman are assumed to be equal to the after-shock values behind a normal compression wave. Values after the shock can be found from Normal Shock Tables which are found in most textbooks pertaining to gas dynamics or high-speed aerodynamics. Appropriate after-shock values determined from the Normal Shock Tables can then be substituted into equation (2) to calculate dynamic pressure behind the shock wave.
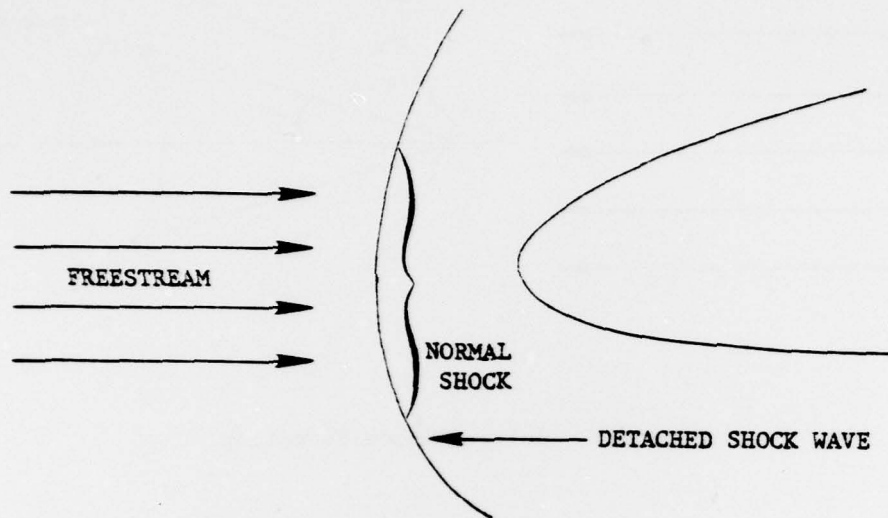
Figure 1 - Detached Shock Wave

NORMAL SHOCK

$$M_1, V_1 \rightarrow \lessgtr M_2, V_2 \rightarrow$$

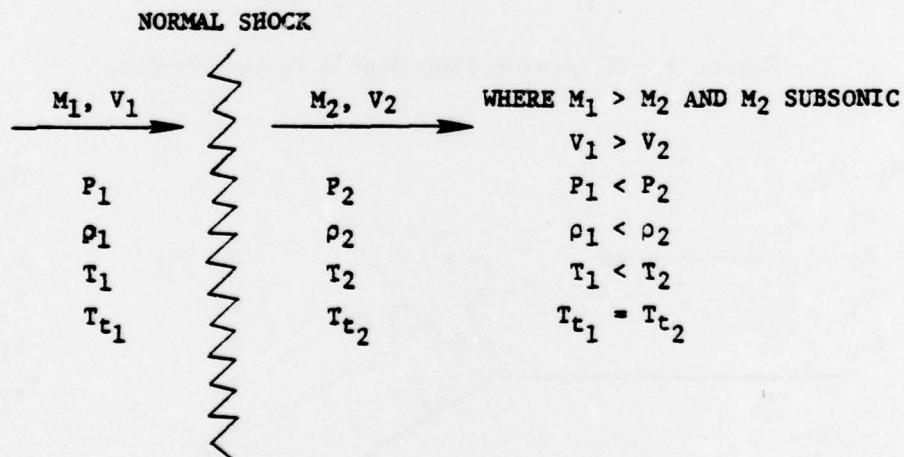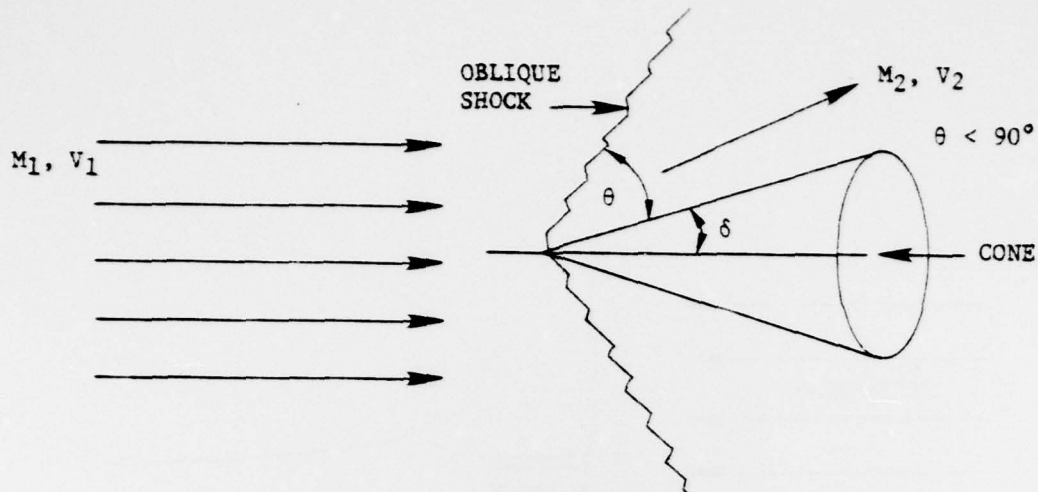|		WHERE $M_1 > M_2$ AND M_2 SUBSONIC
		$V_1 > V_2$
P_1	P_2	$P_1 < P_2$
ρ_1	ρ_2	$\rho_1 < \rho_2$
T_1	T_2	$T_1 < T_2$
T_{t_1}	T_{t_2}	$T_{t_1} = T_{t_2}$

Figure 2 - Normal Shock Characteristics

Figure 3 - Oblique Shock Formation
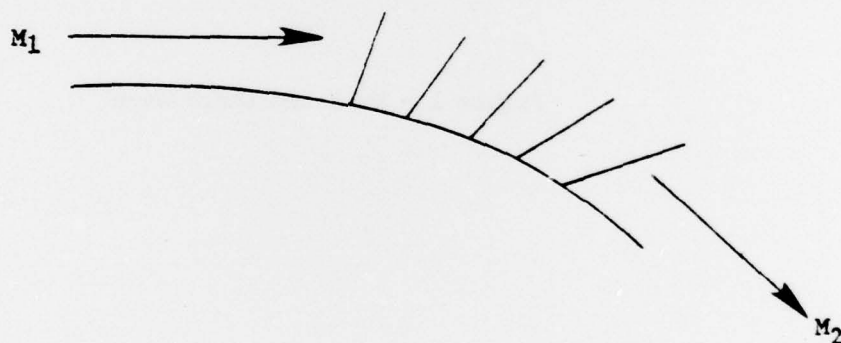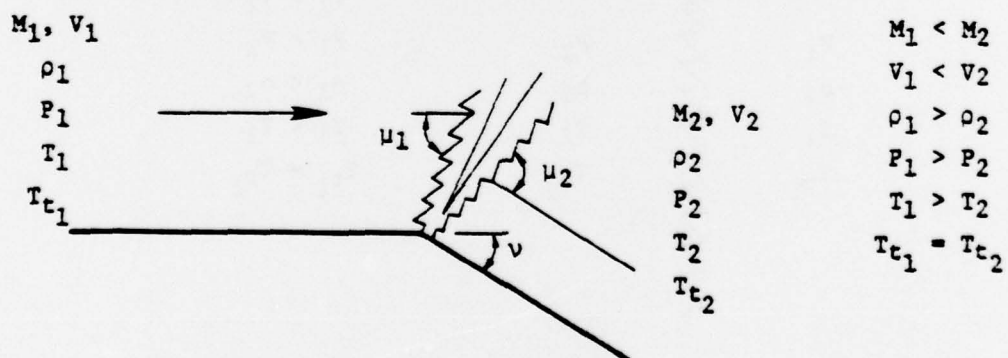

Figure 4 - Expansion Flow Over a Convex Surface

Figure 5 - Expansion Characteristics

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DYNAMIC PRESSURE CURVES (See Appendix A)

In appendix A, q curves are plotted with respect to altitude (sea level to 40,000 feet) and Mach No. (.2 to 2.0). It is assumed that the shock formation is a detached normal shock in front of a blunt body. Figure A-1 relates equivalent air speed (EAS) to Mach number, altitude, and true speed (i.e. corresponding speed at sea level). Figure A-1 can be used in conjunction with figures A-2 through A-11 to find q values for a specified air speed. Figure A-12 is a compilation of figures A-1 thru A-11 which indicates dynamic pressure intensities for Mach 0.5 to Mach 2.0 for a range of altitudes up to 60,000 ft. When the air speed and altitude is known, then the q force can be determined from one of the figures in appendix A. For example, assume the q value is needed for 300 Kn EAS at 20,000 ft. altitude; from figure A-1, for 300 Kn EAS at 20,000 ft., the corresponding Mach number (at 20,000 ft.) is approximately 0.65. The corresponding q value can be determined from figure A-2 (subsonic q curves) or figure A-7 (q curve at 20,000 ft.); in this example, the q value is estimated to be approximately 350 lb/sq. ft.

Consider another example using supersonic airspeed. Assume the equivalent airspeed is 600 Kn EAS at 20,000 ft. From figure A-1, the Mach number is determined to be about 1.34. Now the q value must be determined from figure A-7 (q at 20,000 ft.). Since the Mach number is greater than 1.0, it is the q value after the shock which affects the ejected crewman and ejection system. In this example, the value for q after the shock is approximately 900 lb/sq. ft.

It is interesting to note that the q curves are essentially flat from Mach 1.0 to Mach 1.20; actually, there is a very slight decrease in the value of q between Mach 1.0 and Mach 1.18 and then q increases slowly as Mach No. increases to Mach 2.0. Again, it must be remembered that a detached normal shock in front of a blunt body is a shock formation (the crewman is being assumed).

The resulting pressure changes across the normal compression shock not only cause a decrease in dynamic pressure, but also a decrease in total (stagnation) pressure and an increase in static pressure. For relatively intense shock waves (e.g. Mach 2), the static pressure behind the shock wave may be about four times greater than the atmospheric pressure. This increase should be no problem to the ejecting crewman; the greater concern is still the dynamic pressure.

WIND DRAG DECELERATION AND WINDBLAST DURATION

The exposure time to windblast decays rapidly during the first several seconds of ejection. Within approximately 3 seconds after ejection at sonic speed, the crewman experiences a windblast pressure of approximately 50 percent of the initial windblast pressure. The deterioration of windblast pressure due to wind-drag deceleration depends on frontal drag areas, drag coefficients, weight, deployment of the ejection recovery system, and altitude.

REFERENCES

(a) Koethe, A.M. and Schetzer, J.D.; Foundation of Aerodynamics, John Wiley & Sons, Inc., New York, 1950.

(b) Dommasch, D.O., et al; _Airplane Aerodynamics_, Pitman Pub. Co., New York, 1967.

ACKNOWLEDGEMENTS

APPENDIX A

DYNAMIC PRESSURE CURVES

STRATOSPHERE   TROPOSPHERE
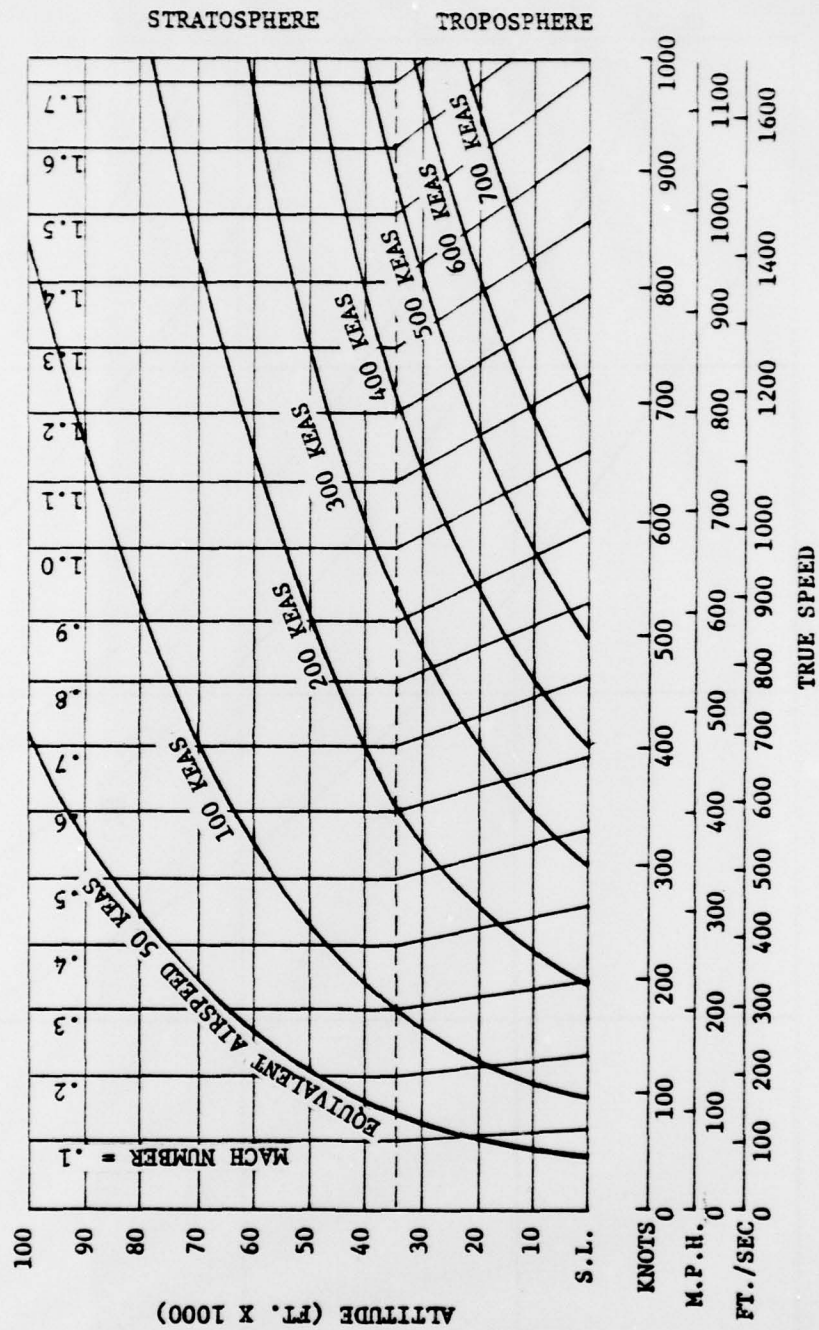
Figure A-1 - Altitude/Airspeed Chart
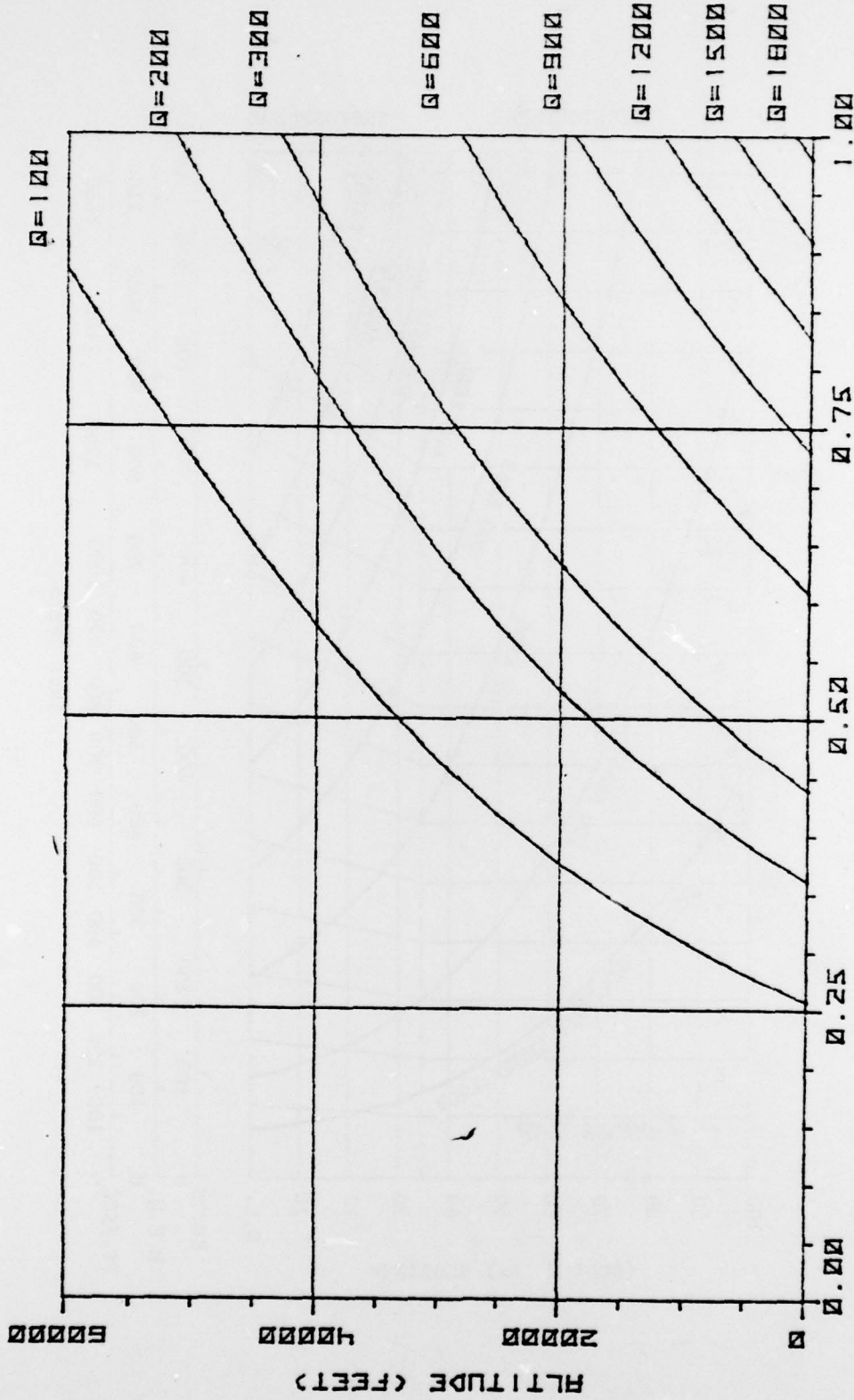
Figure A-2 - Subsonic Windblast Pressure Curves
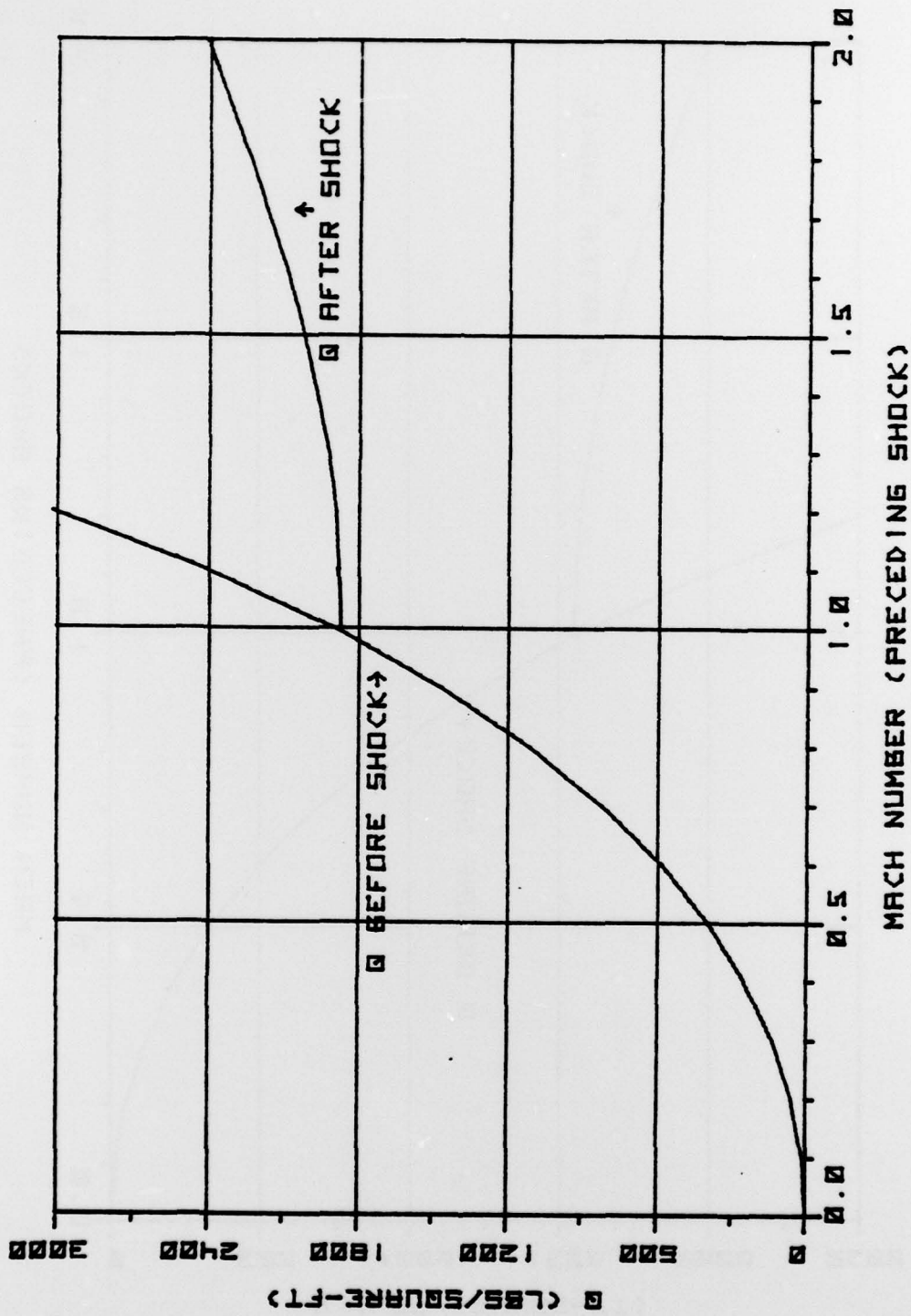
Figure A-3 - Ejection Seat Dynamic Pressure - Sea Level

MACH NUMBER (PRECEDING SHOCK)
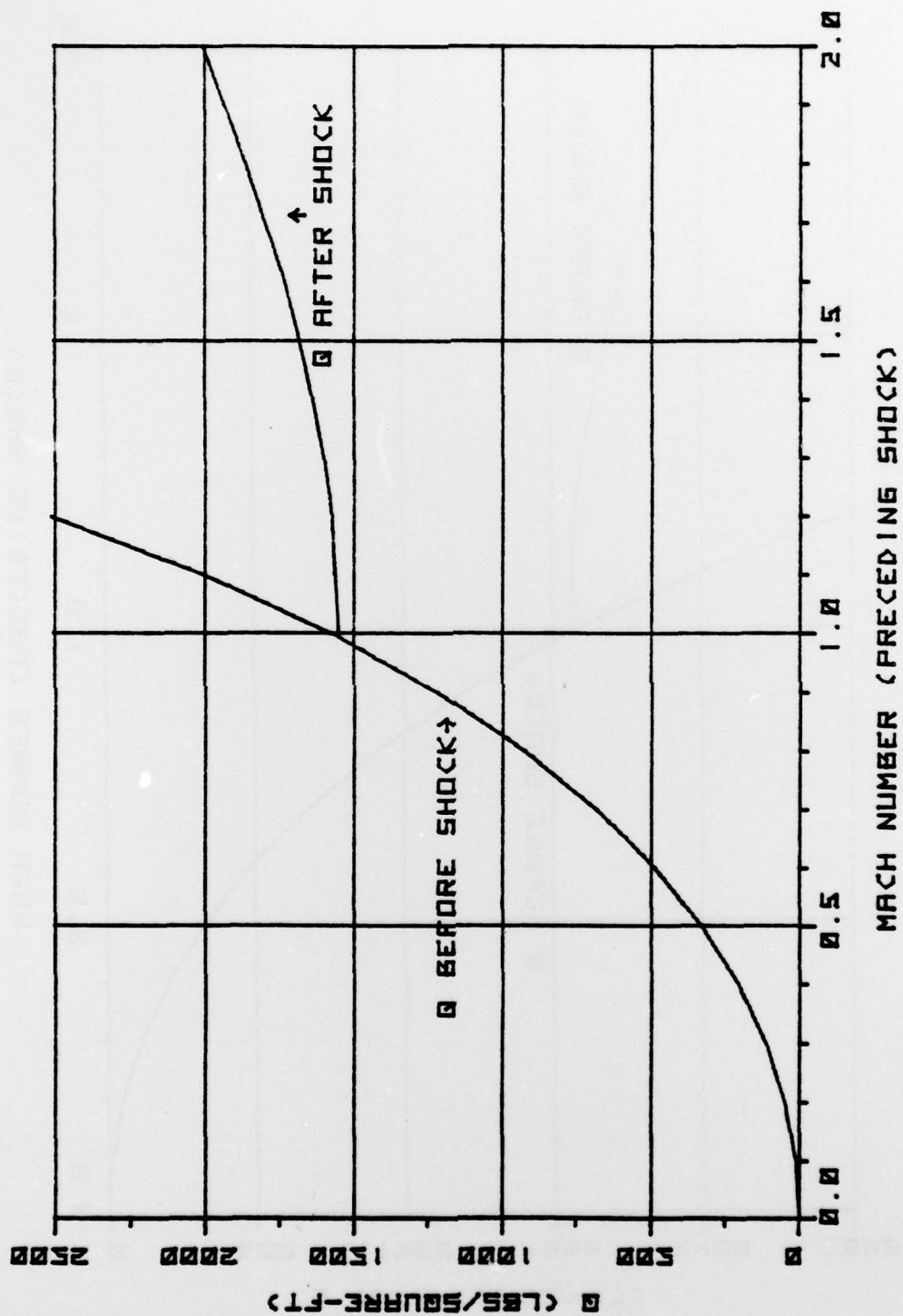
Figure A-4 - Ejection Seat Dynamic Pressure - 5,000 Ft.

MACH NUMBER (PRECEDING SHOCK)
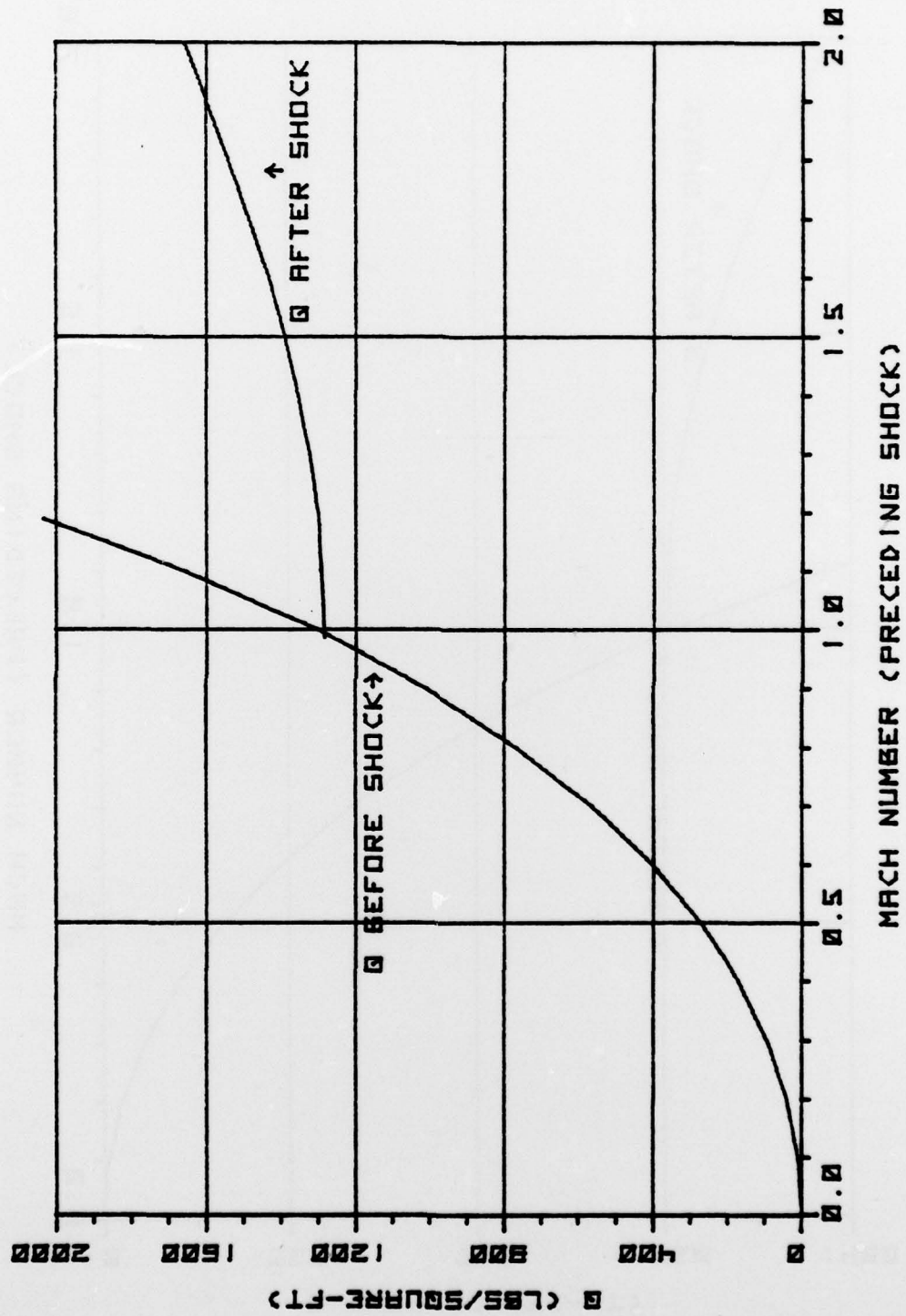
Figure A-5 – Ejection Seat Dynamic Pressure – 10,000 Ft.

A-7

MACH NUMBER (PRECEDING SHOCK)
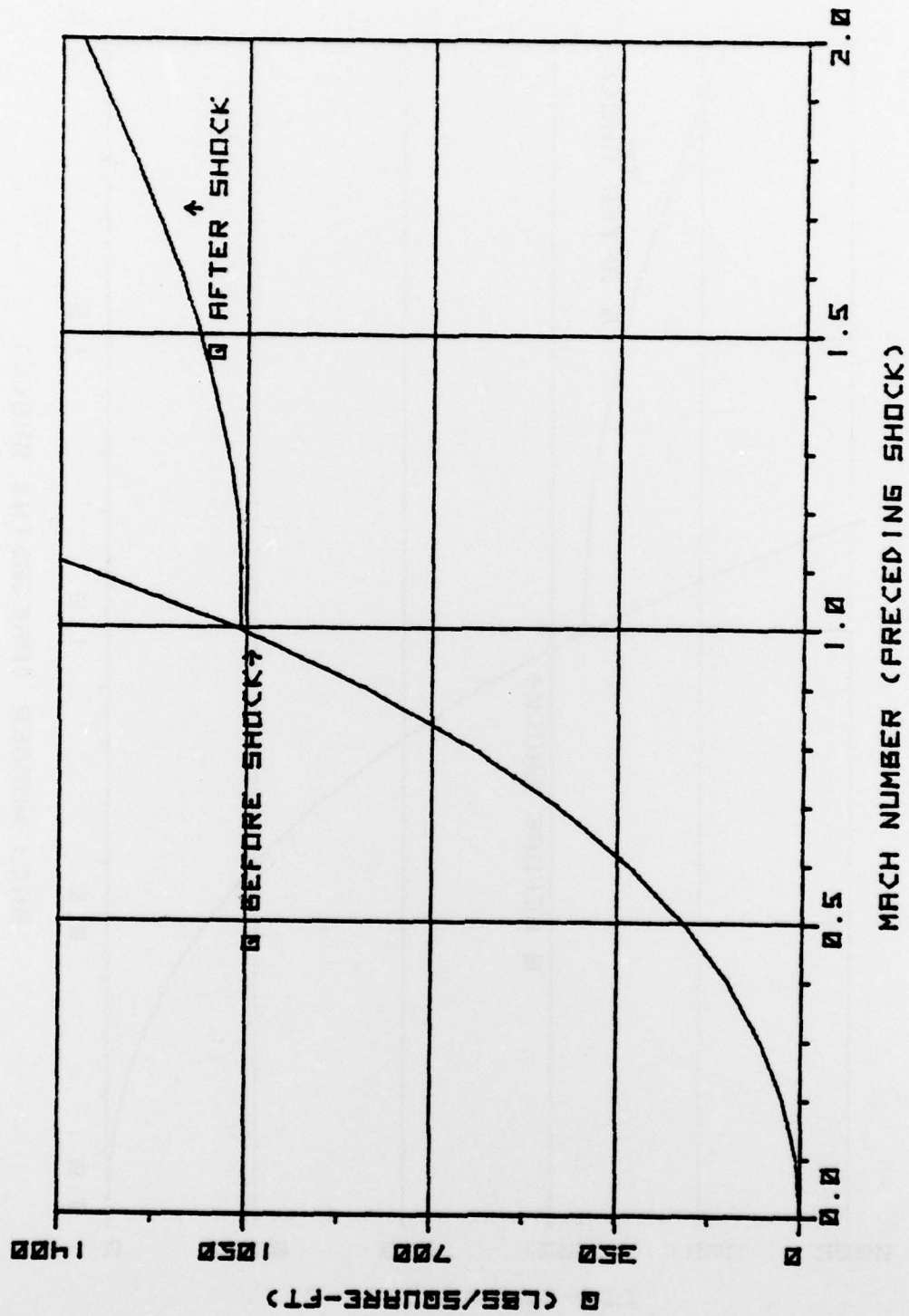
Figure A-6 - Ejection Seat Dynamic Pressure - 15,000 Ft.

MACH NUMBER (PRECEDING SHOCK)
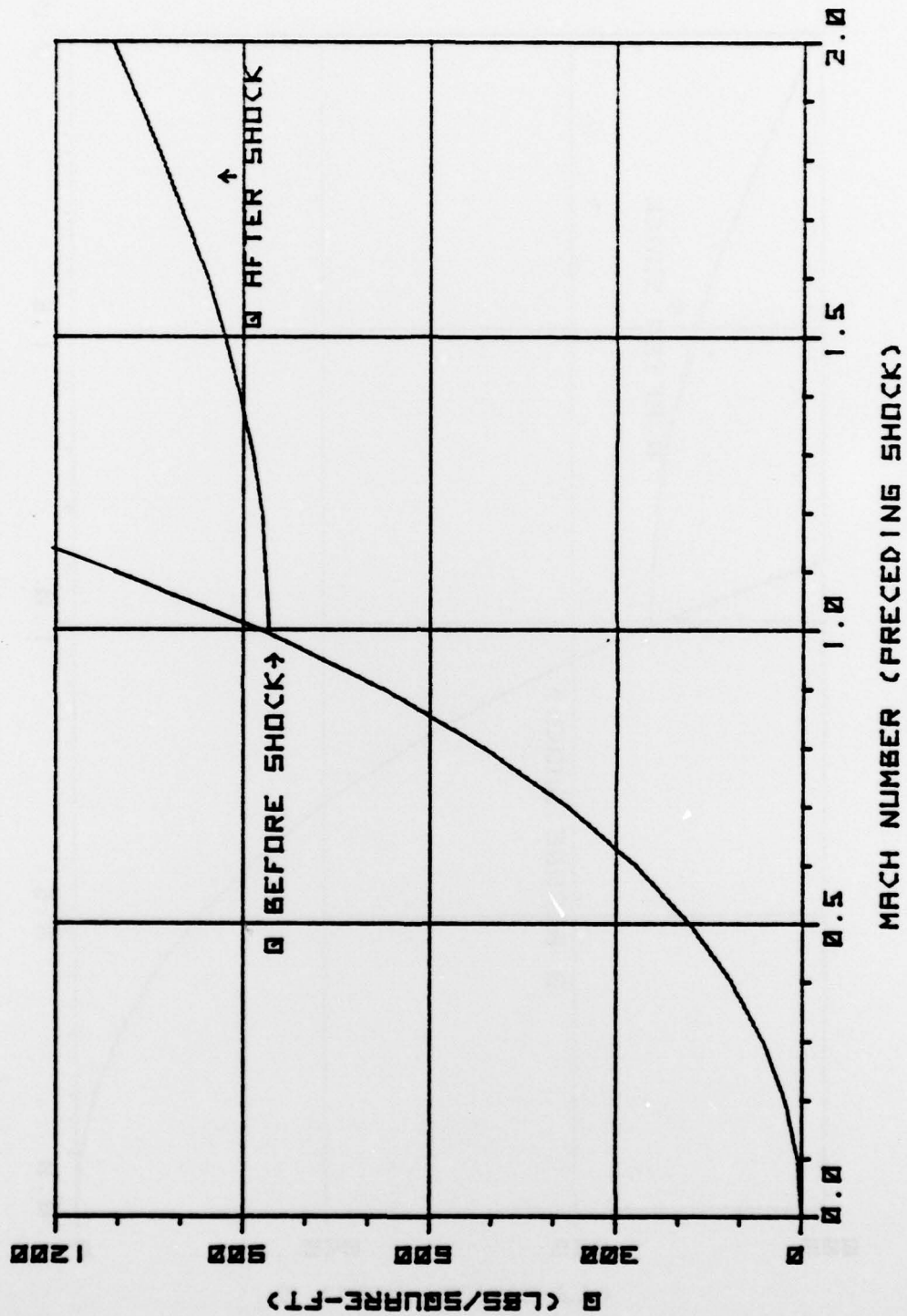
Figure A-7 - Ejection Seat Dynamic Pressure - 20,000 Ft.

MACH NUMBER (PRECEDING SHOCK)

Q (LBS/SQUARE-FT)
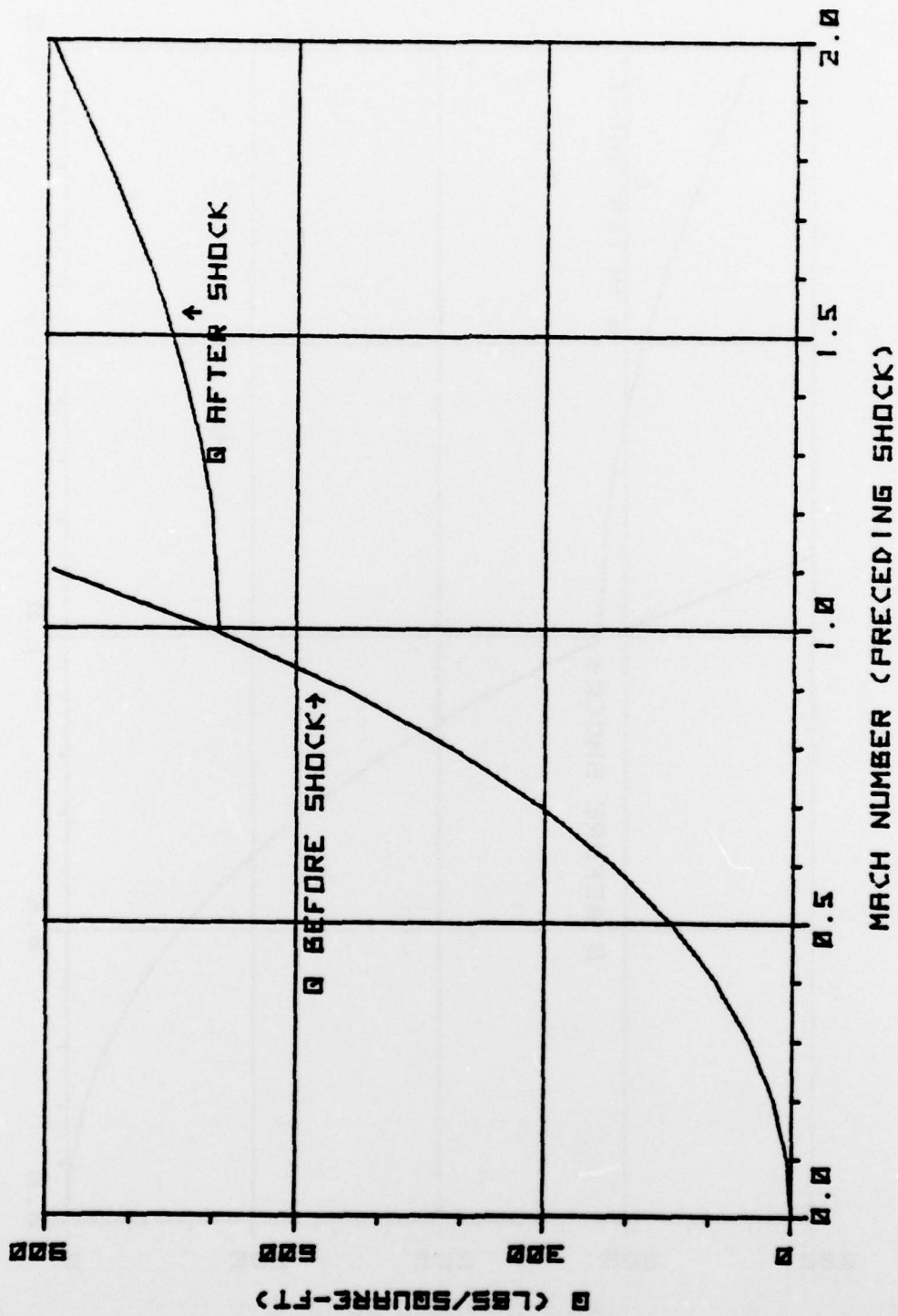
Figure A-8 - Ejection Seat Dynamic Pressure - 25,000 Ft.
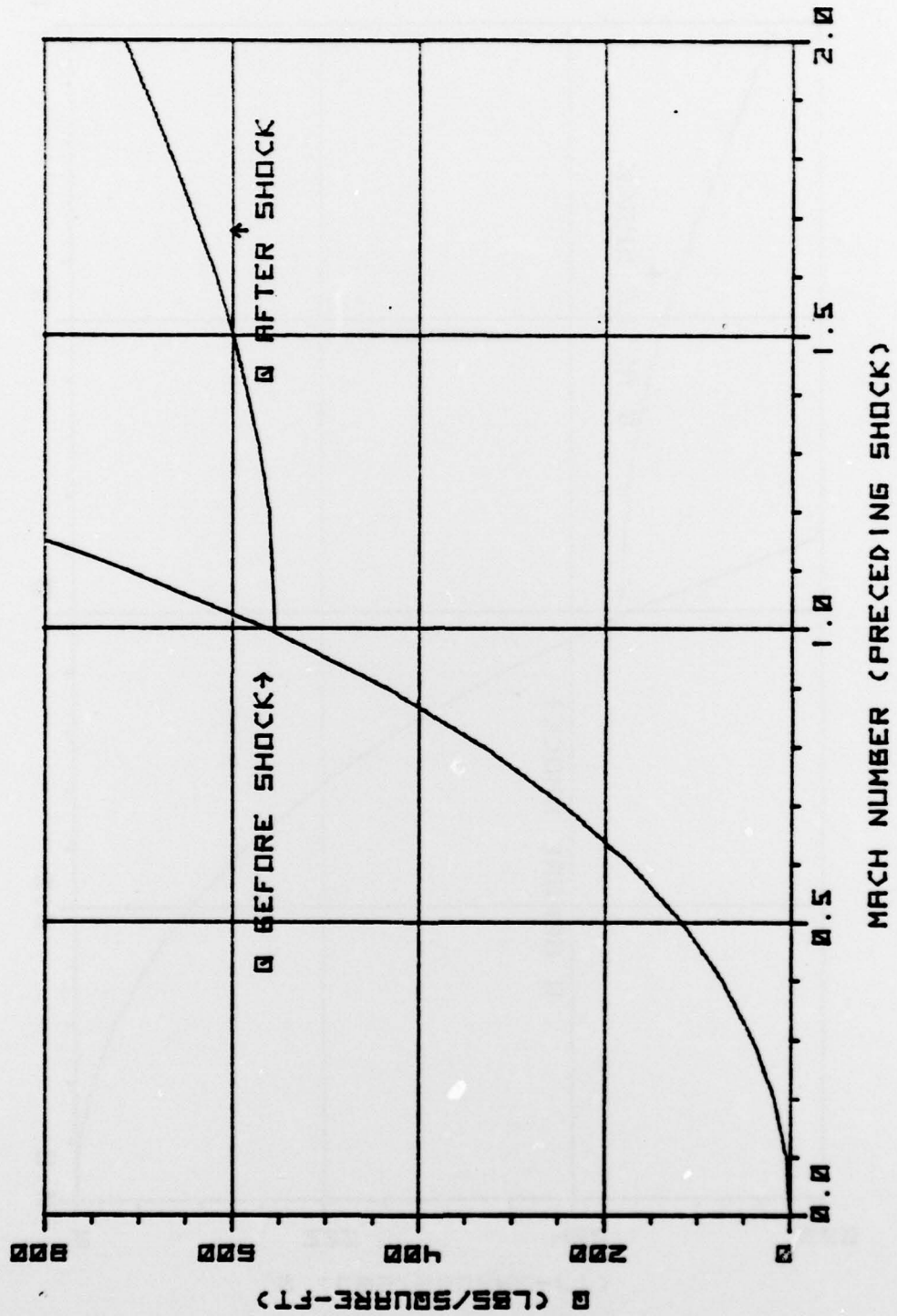
Figure A-9 - Ejection Seat Dynamic Pressure - 30,000 Ft.
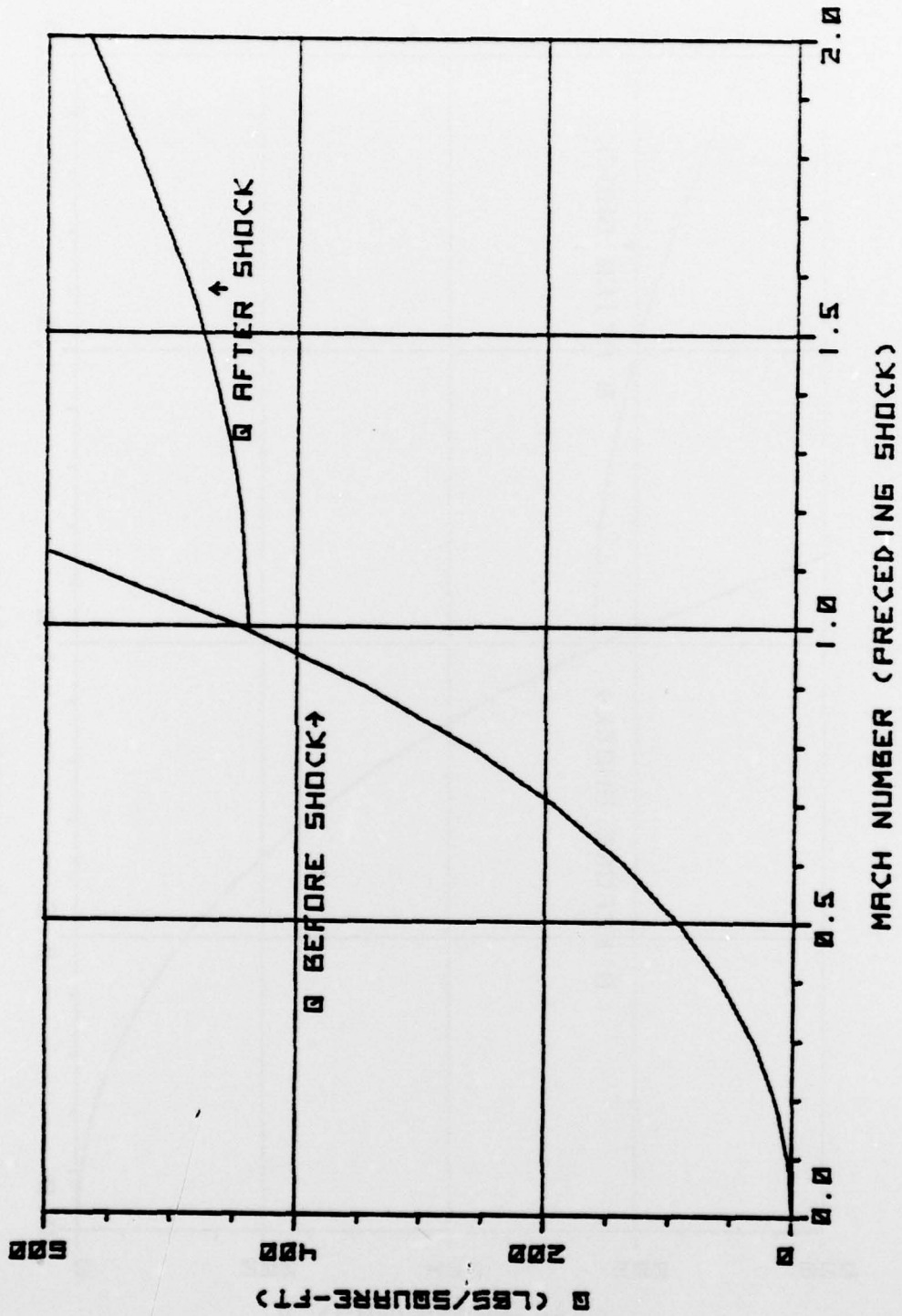
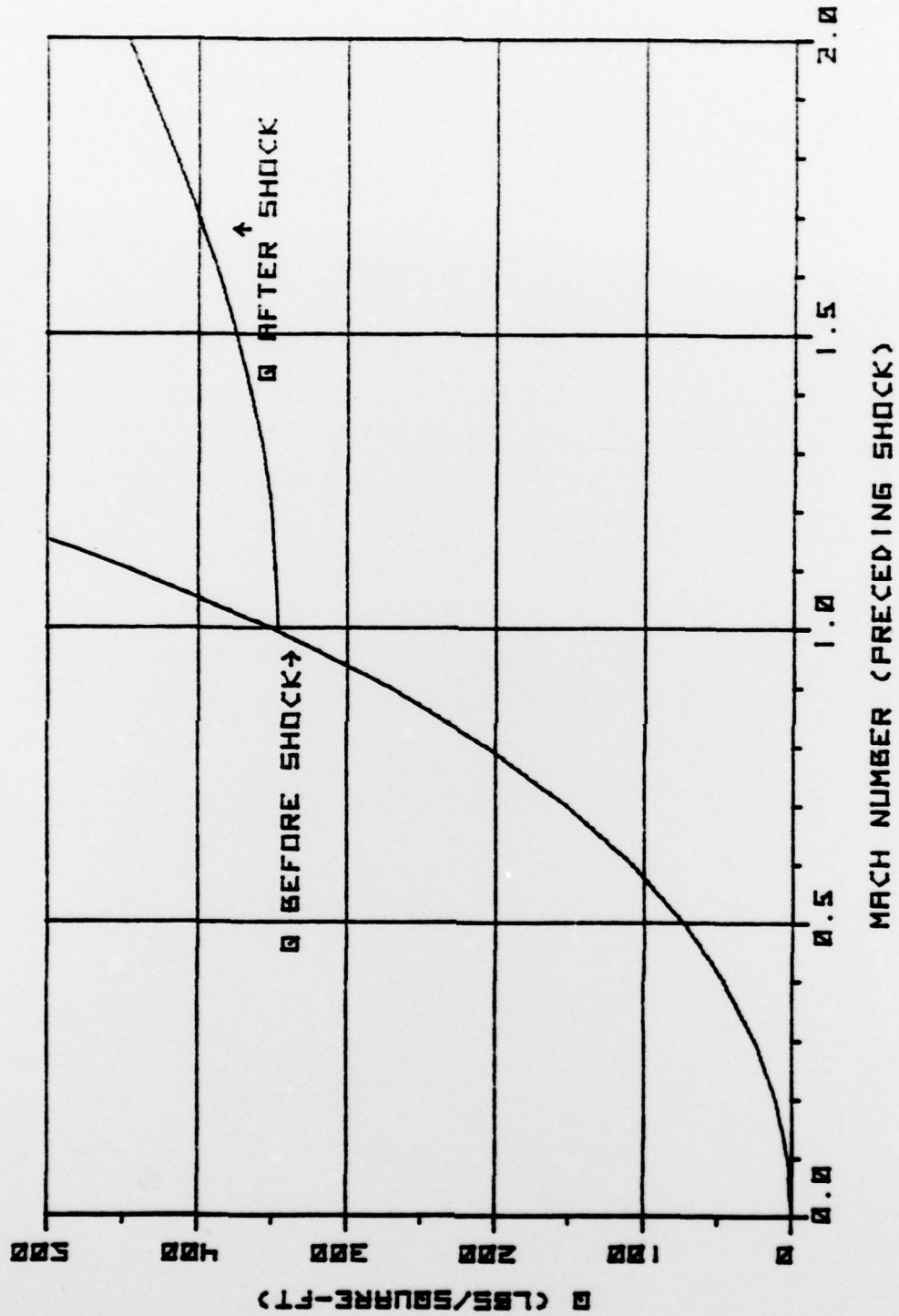Figure A-10 - Ejection Seat Dynamic Pressure - 35,000 Ft.

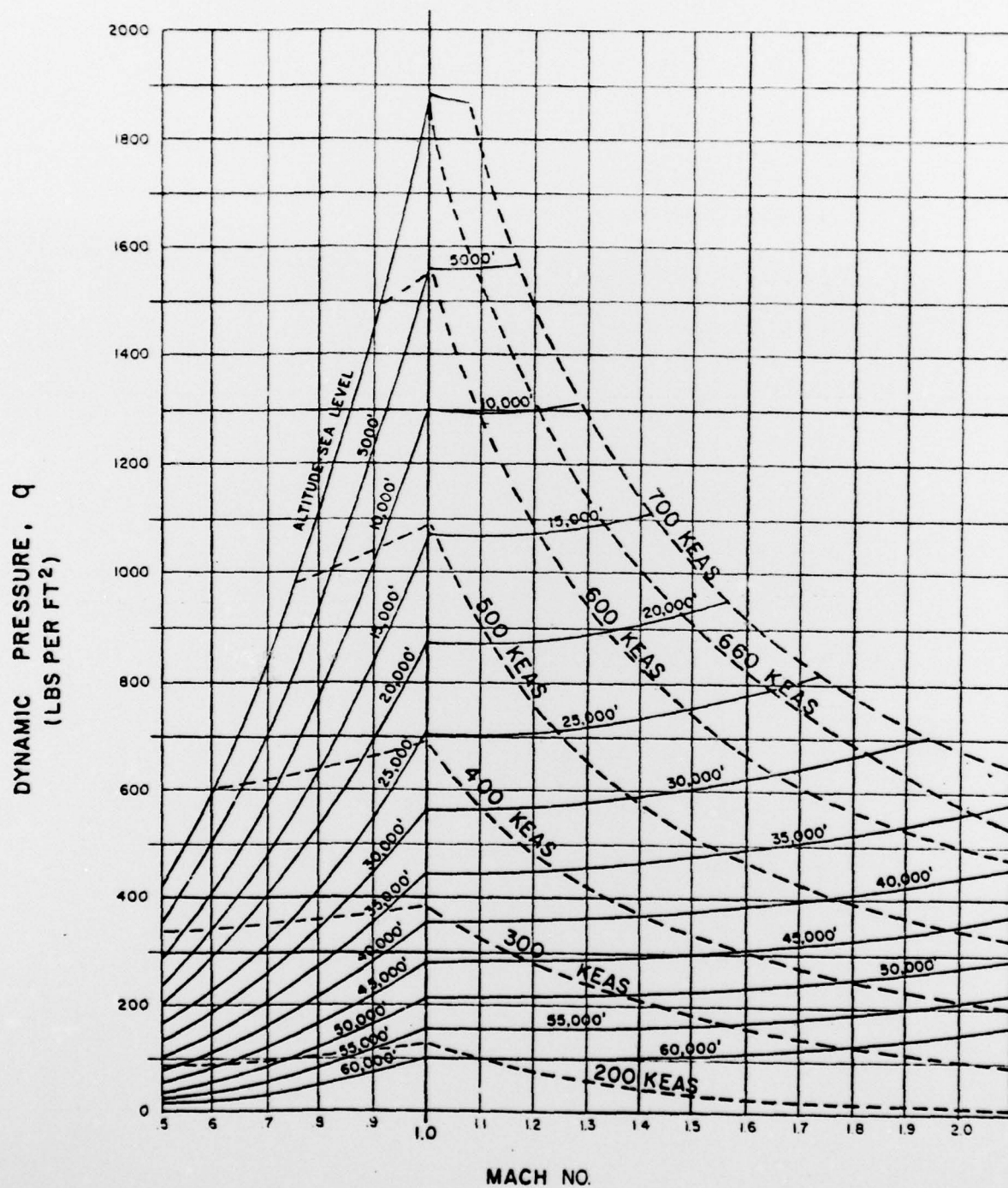Figure A-11 - Ejection Seat Dynamic Pressure - 40,000 Ft.

Figure A-12 – Dynamic Pressure vs Mach No., Airspeed Keas & Altitude (Ft)
For
ICAO Standard Atmosphere